Light Interferometer for Measurement of the Gravitational Behavior of Antimatter

G. Vinelli[1,2,3], **F. Castelli**[4,5]; **R. Ferragut**[5,6]; **M. Romé**[4,5]; **M Sacerdoti**[6]; **L. Salvi**[1,2,3]; **V. Toso**[4,5]; **M. Giammarchi**[5]; **G. Rosi**[1,2]; **G. M. Tino**[1,2,3]

[1]Department of Physics and Astronomy, Università di Firenze, Via Sansone 1, 50019 Florence, Italy
[2]INFN, Sezione di Firenze, Via Sansone 1, 50019 Florence, Italy
[3]LENS, Università di Firenze, Via Nello Carrara 1, 50019 Sesto Fiorentino, Italy
[4]Department of Physics, Università degli Studi di Milano, Via Celoria 16, 20133 Milano, Italy
[5]INFN, Sezione di Milano, Via Celoria 16, 20133 Milano, Italy
[6]L-NESS and Department of Physics, Politecnico di Milano, Via Anzani 42, 22100 Como, Italy

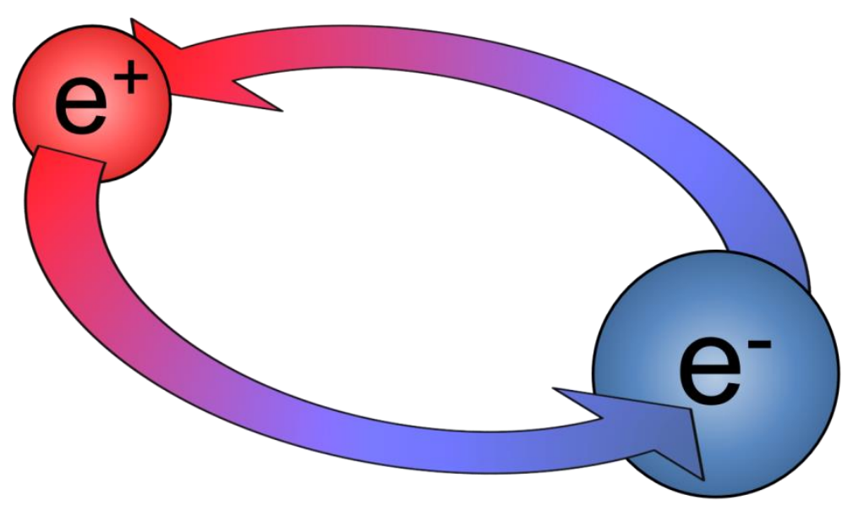
Contact information: giuseppe.vinelli@unifi.it

Abstract

The QUPLAS (QUantum interferometry and gravitation with Positrons and LASers) experiment aims to test fundamental physical laws with antimatter by measuring the **Positronium (Ps) fall in the Earth's gravitational field**. Such measurement would represent a test of the **Einstein Equivalence Principle and the CPT symmetry** and is further motivated by the lack of information on antimatter behavior in the gravitational field.
The setup and techniques of the experiment involve two phases of preparation and interference of the positronium beam. **I will discuss the design, simulation and optimization of the Large Momentum Transfer (LMT) Mach-Zehnder interferometer** [1] used in the final stage of the experiment to reveal the influence of the Earth's gravitational field through the relationship that binds the phase shift of the wave function of Ps to the gravitational acceleration: $\Delta\phi=k_{eff}gT^2$ [2]. By simulating the interferometer, it was possible to estimate its efficiency, contrast and signal acquisition times as well as determining fundamental operating parameters such as the size, shape and power of the laser pulses. These results will be shown in the exhibition.

Positronium (Ps)

- ❑ Matter-antimatter (electron-positron) quasi-stable bound system
- ❑ Simplest purely leptonic electromagnetically bound state: well described by QED, perfect probe for new physics



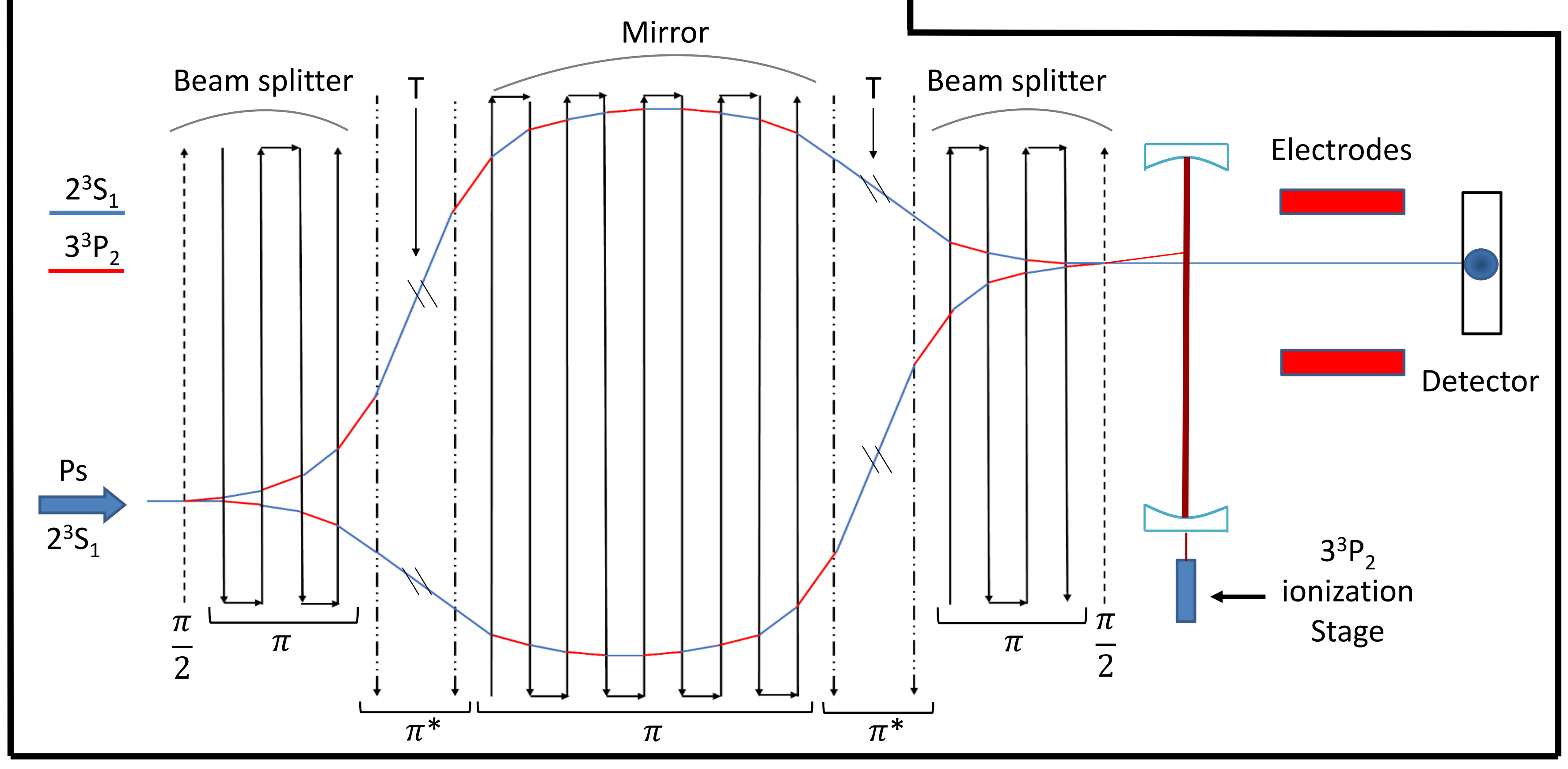
Constraints:

1) Reduced lifetimes:
   - 1^1S_0 (para-Ps): 0,125 ns
   - 1^3S_1 (ortho-Ps): 142 ns
   - 2^3S_1: 1,3 µs
2) Annihilation by matter-antimatter contact
3) Neutrally charged: unresponsive to focusing electrodes

1) High Ps velocity needed
2) Ultra High Vacuum needed
3) Ps ion needed

The Interferometer

- **23 laser pulses** split and recombine Ps wave function that accumulates a phase shift proportional to gravity $\Delta\phi=k_{eff}gT^2$, where $k_{eff}=10\frac{2\pi}{\lambda_{laser}}$ and the propagation time is T≈0.4 µs
- The π^* pulse changes the state in one arm to let Ps propagate in the long living 2^3S_1 state
- The ionization stage ionizes the $3^3P_{2:}$ no spatial separation is needed at the detector. The electrodes remove the residual e^+ and e^-
- To counter the laser phase noise, a double measurement will be done [3]

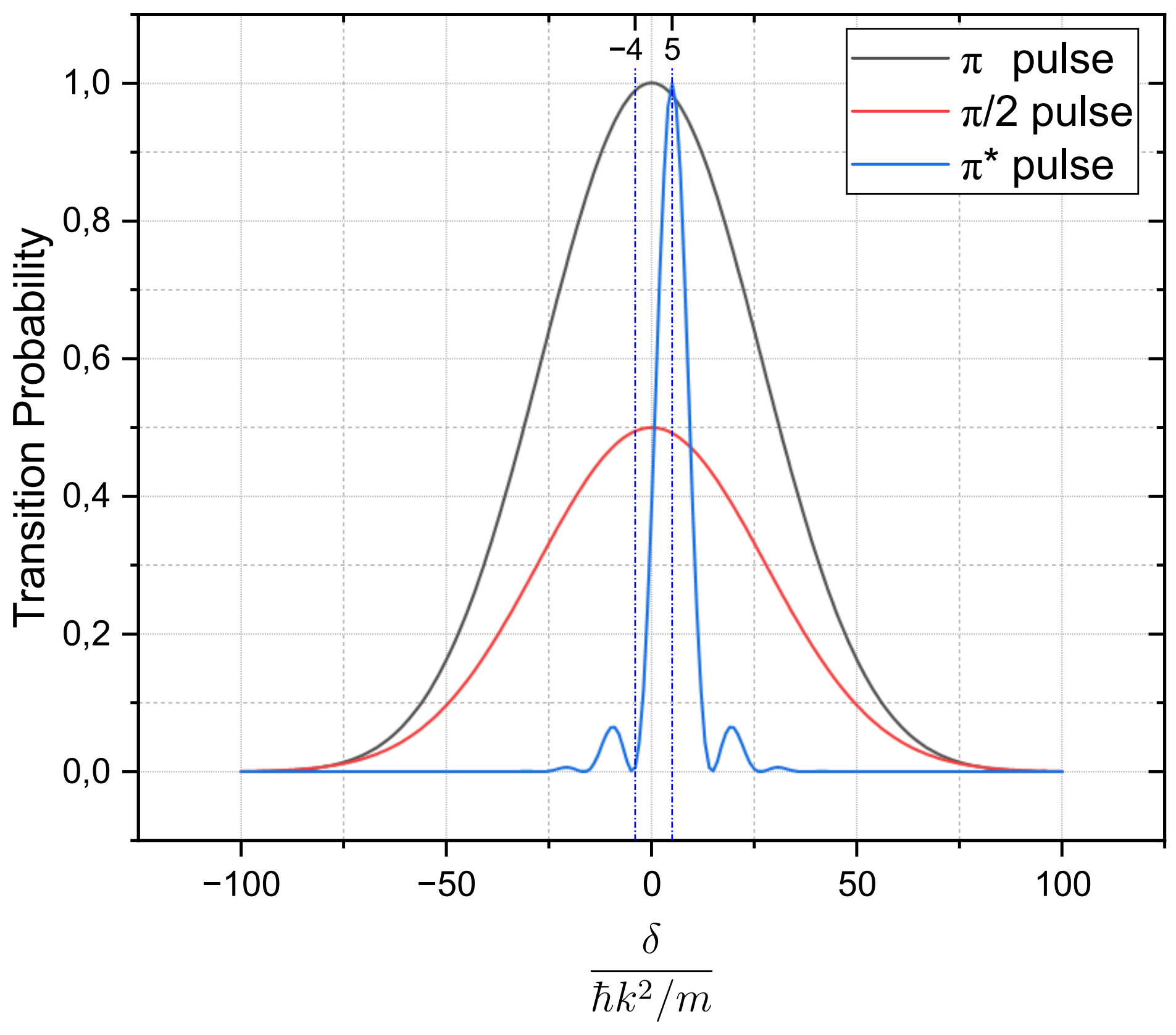


Simulation

- State transition after the interaction with a Gaussian pulse is modeled by the set of differential equations solved by the Runge-Kutta method:

$$\begin{cases} \dot{c}_g = \dfrac{-i\Omega(t)}{2} c_e e^{i(\delta t-\varphi)} \\ \dot{c}_e = \dfrac{-i\Omega(t)}{2} c_g e^{-i(\delta t-\varphi)} \end{cases}$$

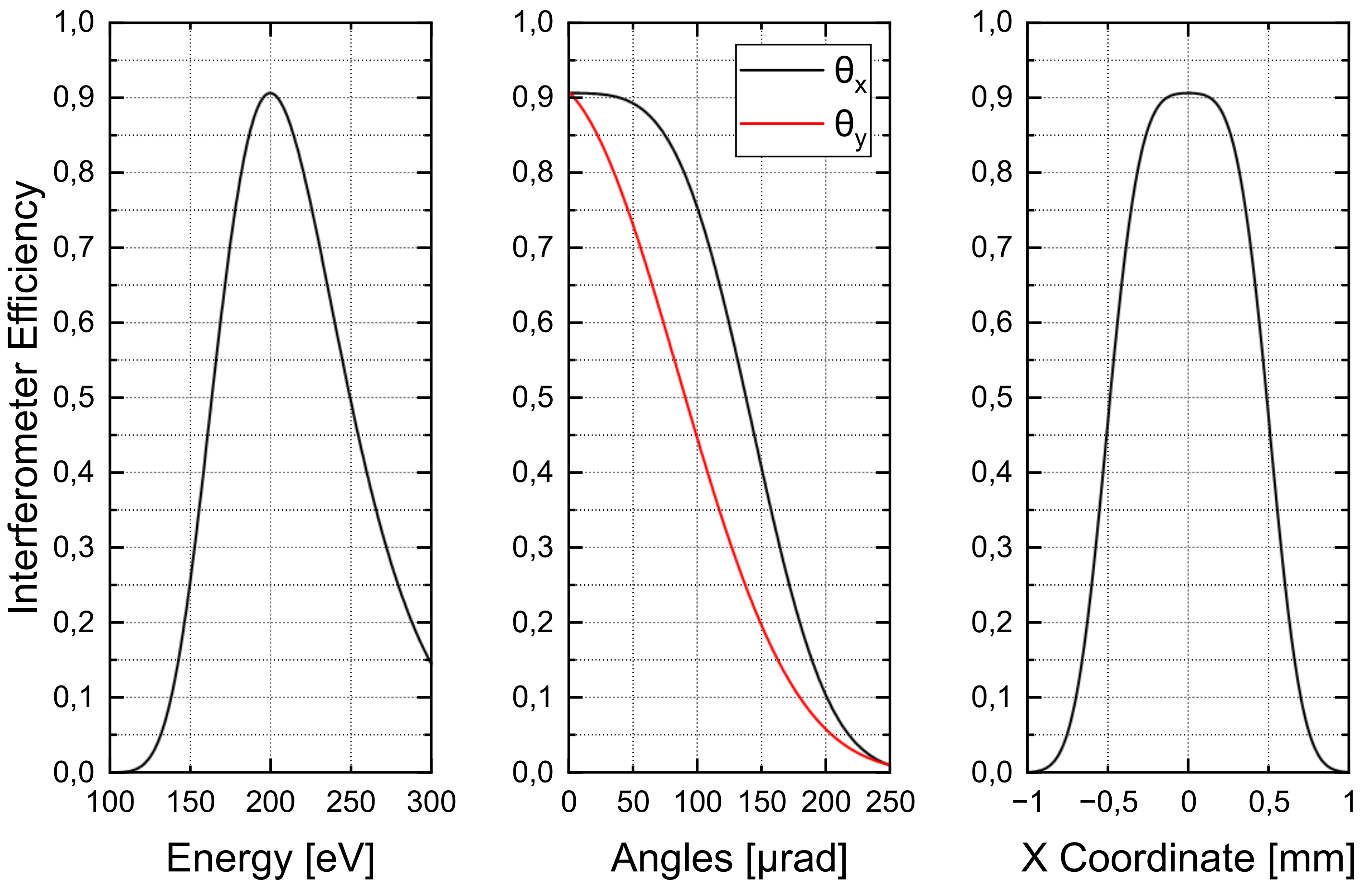
- **Quantomechanical simulation**: the Ps wave function splits in two after a pulse, generating more than 8×10^6 (parasitic) states that can interfere with each other.
- **Semi-classical simulation**: the atom is treated as a point like particle but the interaction with the pulses is still described by the differential equations
- **Monte Carlo simulation**: based on the semi-classical approach, the interferometer has been tested for different Ps energies, entrance angles and positions.

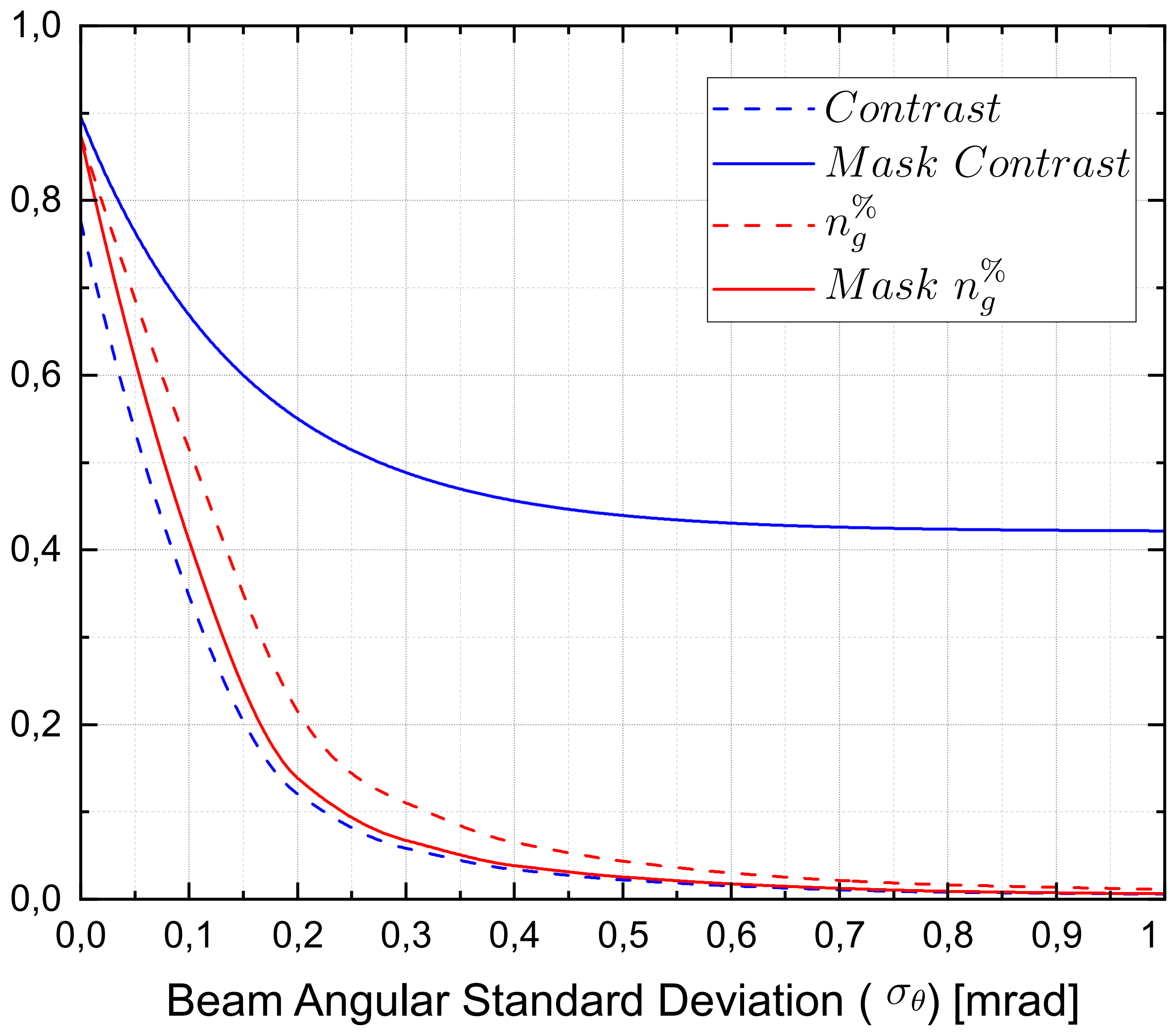


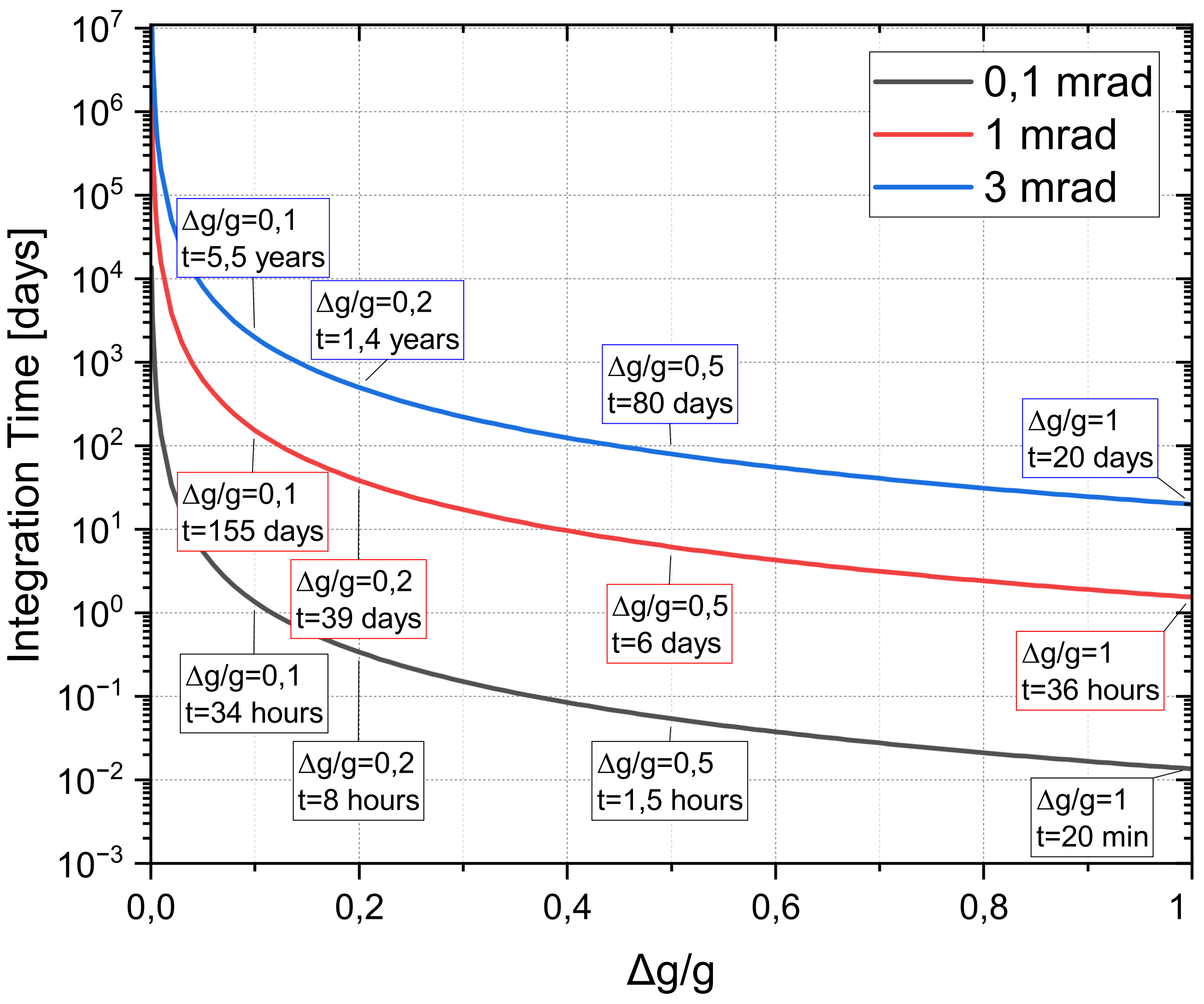
Transition probability between the n=2 and n=3 states as a function of the ratio between the Doppler and the momentum transferred by the laser.

Results

- The **parasitic states do not interfere with the gravitational information carriers**, validating the results of the semiclassical approach
- **Entrance angles are critical** parameters for the interferometer efficiency
- It is convenient to use **the interferometer as a collimator**: a mask before the detector selects the entry angles, rejects most of the noise and keeps **the contrast, C, constant and about 0.4**
- The interferometer shows a ***self-cleaning action*** by automatically rejecting the noise
- The signal integration time is $t=\left(\frac{\sqrt{2}}{20kT^2\Delta gC}\right)^2\frac{1}{\varepsilon\phi_{Ps}}$ where $\phi_{Ps}\approx10^6$ Ps/s is the Ps flux and Δg is the sensitivity. An estimation of t as a function of the desired sensitivity has been obtained







Conclusions

- A **Large Momentum Transfer Interferometer** for the measurement of the Positronium fall in the Earth's gravitational field has been designed and simulated
- The simulation highlighted the criticality of some parameters of the Ps beam, leading to the **design of new detection and collimation methods**
- This analysis checked **the feasibility of the experiment** by estimating **the signal acquisition time** as a function of the required sensitivity. Theory suggests that a 20% value of the relative error of the g measurement will be already of interest [4]. Moreover, a moderate 50% relative error will exclude the antigravity hypothesis. Thus, in conclusion, **less than 1 year of data taking** would be enough to **measure the gravitational effect on antimatter for the first time**.

References

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